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Can carbon footprint serve as proxy of the environmental burden from urban consumption patterns?

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Abstract: Carbon footprint (CFP) is widely applied as an indicator when assessing environmental sustainability of products and services. The objective of the present study is to evaluate the validity

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31 of CFP as overall environmental indicator for representing the environmental burden of residents
32 from urbanized areas. Applying four different Life Cycle Impact Assessment (LCIA) methods
33 environmental impact profiles were determined for the consumption patterns of 1281 Danish urban
34 residents. Six main consumption components were distinguished including road transport, air travel,
35 food, accommodation (covering consumption of materials for the construction of dwellings) and use
36 of energy in terms of thermal energy, and electricity. The results for the individual consumption
37 components showed a strong correlation between CFP and nearly all other impact indicators for all
38 the applied LCIA methods. However, upon aggregation of the indicator results across consumption
39 components, the impact indicators for the total consumption showed no significant correlation
40 between CFP and the other impact scores for any of the four impact assessment methods. These
41 findings suggest that while CFP can be a good indicator of the environmental burden associated with
42 specific activities, this is not the case for more complex activities (such as consumption patterns
43 related to urban life styles). This conclusion discourages the use of CFP as sustainability measure in
44 relation to regulation of private or public consumption.

45

46 **Keywords:** Urban resource consumption; carbon footprint; Life cycle assessment; sustainability; urban
47 systems

48

49 **1. Introduction**

50 The increasing focus on the environmental impacts associated with resource consumption and other
51 anthropogenic activities have led to the development of a multitude of approaches for estimating
52 environmental footprints. Carbon footprint, water footprint, material footprint and energy intensity
53 *etc.* are some of the approaches used to account for environmental impacts(Čuček et al., 2012; Herva
54 et al., 2011; Singh et al., 2009) assessed in the various footprints. Life Cycle Assessment (LCA) is
55 one of the most widely used and a well-suited tools for quantifying environmental footprints even for
56 complex systems such as systems closely associated with human choices and preferences and hence
57 systems containing subjective elements.

58 Since the introduction of the methodology, LCA has undergone continuous development and
59 refinement. Rebitzer et al. (2004) and Pennington et al. (2004) both provide exhaustive
60 documentation on the detailed framework of LCA. The LCA field is vast and base on inputs from
61 multiple scientific disciplines such as chemical fate and transport modeling, exposures assessments,
62 effect/damage modeling on ecosystem and human health. Hence, there has been continuous inclusion
63 of new knowledge, concepts and development of methodologies. Finnveden et al. (2009) and Guinée
64 et al. (2011) reported historic and recent developments in LCA as well future requirements and
65 challenges.

66 Although, the LCA is widely used for assessing products and services there are still unresolved issues,
67 which need to be addressed. Reap et al. (2008a, 2008b) documented some of the unresolved issues in
68 LCA while Udo de Haes et al. (2004) illustrated some of the limitations of LCA. The majority of the
69 issues are related to the disagreement on the common choice of functional unit, system boundary
70 (Suh, 2006; Tillman et al., 1998), allocation methods(Azapagica and Cliftb, 1999; Ekvall and
71 Finnveden, 2001) and LCIA methodologies. Choices made in an LCA relating to one or more of these
72 issues and limitations introduce a subjective element to any LCA and makes generally difficult to
73 compare LCA studies even if conducted on similar products or services.

74 LCA requires vast amounts of data, software, specialized skills and time all limiting the application
75 of LCA. In addition, the assessment method requires data analyst skills on expert level in order to
76 fully understand and interpret the results provided by an LCA. These complexity challenges posed
77 by the LCA methodology itself and the results here of makes it difficult to communicate LCA based
78 results to the public and stakeholders (Weidema et al., 2008) without introducing simplifying however

79 subjective assessment layers such as e.g. weighting and/or an additional damage modelling layer
80 further increasing the assessment uncertainty. No matter if one chooses to apply weighting and/or
81 damage modelling the credibility of an LCA will thus be compromised either due to introduction of
82 subjective elements and/or increased uncertainty.

83 Due to communication hurdles caused by the complexity of many LCA results, researchers, policy
84 makers, experts, and industries have been looking for a way to bypass weighting and damage
85 modelling in LCA in order to increase the communicability of LCA results. A solution could be a
86 proxy indicator(Huijbregts et al., 2010; Udo de Haes, 2006), a single environmental impact indicator
87 intended to serve as a proxy for all the other possible environmental burdens (and hence also the
88 overall environmental sustainability performance) associated with products, services and
89 technologies.

90 Various studies have previously explored and attempted to validate the use of single point indicators
91 (including carbon footprint) to represent overall environmental impacts. Bösch et al. (2007) correlated
92 Cumulative Exergy Demand (CExD) indicators with CML 2001 and Ecoindicator (EI) 99
93 characterization factors for energetic and non-energetic resources and discovered weak or no
94 correlation between these. Bao and Multani (2007) carried out a similar analysis on 47 products
95 (industrial as well as consumer products) where correlations between life time energy consumption
96 and environmental impacts estimated using LCA were explored. The study yielded clear correlation
97 between the life cycle energy consumption and LCA results, for most of the products.

98 Huijbregts et al. (2010) conducted a comparative assessment of the Cumulative Energy Demand
99 (CED) of 498 commodities (metals, glass, paper and cardboard, organic and inorganic chemicals,
100 agricultural products, construction materials, and plastics) and six frequently applied environmental
101 life cycle assessment based indicators [Ecological Footprint (EF), Cumulative Exergy Extraction
102 from the Natural Environment (CEENE), Carbon Footprint (CFP), Environmental Priority Strategy
103 (EPS), Ecological Scarcity (ES) and Eco-Indicator 99 (EI 99)]. The study found that CED produces
104 comparable ranking of commodity production impacts compared to all other methods included in the
105 study. The authors further argued that CED could be used as a screening indicator for environmental
106 performance at early product development stages. However, the study also points out that CED may
107 not be a good choice for agricultural products where environmental impacts also are closely
108 associated with non-energy related emissions (e.g. pesticides, nutrients).

109 Berger and Finkbeiner (2011) analyzed correlations between energy and resource consumption based
110 impacts across a multitude of indicators for 100 materials (ores, metals, alloys monomers and
111 polymers, organic intermediates, inorganic intermediates). The study highlighted that there was no
112 significant correlation between indicators assessing resource consumption (i.e. scarce resources,
113 water, land etc.) and pollution driven impacts (toxic impacts categories, eutrophication etc.). The
114 study further suggests that a wide range of impacts need to be evaluated comprehensively in order to
115 appropriately quantify the impacts related to resource consumption. However, a significant
116 correlation was found among resource consumption indicators suggesting a possibility of
117 reducing/aggregating resource consumption dedicated indicators for defining resource use and hence
118 simplifying the LCA result set.

119 Laurent et al. (2010) investigated the use of CFP as overall environmental performance indicator by
120 correlating CFPs with Human Toxicity (HT) impact potentials for selected material production unit
121 processes. The study concludes that HT impacts are not significantly correlated with CFPs and further
122 that the CFP-HT dependencies appear to be material (metallic or non-metallic) specific. The same
123 approach of exploring correlations was further extended in another study to analyze a more diverse
124 and considerable dataset (3954 impact profiles) of products/services (Laurent et al., 2012). This study
125 concluded that CFP may correlate at the overall environmental impacts of mixed products/services;
126 however, a deeper investigation of specific product/service categories did not confirm the correlation
127 between the CFP and environmental impacts (Laurent et al., 2012). This observation led to general
128 recommendations on when CFP may be appropriate and when it cannot be considered appropriate as
129 overall environmental performance indicator. The study recommends that unless CFP has been
130 proven well correlated with other environmental impacts of a given product/service (group) it has to
131 be regarded as a transition (i.e. uncertain) indicator.

132 In the food sector, Rööß et al. (2013) evaluated the use of CFP to represent the overall environmental
133 impacts from animal-rearing and found that the environmental impacts of meat from monogastric
134 animals can be well represented by CFP. However, the study also reported that the same is not the
135 case for meat production from ruminants. Rugani et al. (2013) presents a comprehensive review of
136 CFP studies within the wine sector and recommends that further studies need to be undertaken in
137 order to understand the complex market interactions associated with the entire product system of
138 wine. The complex value chain of wine and associated market interactions makes it dubious to
139 recommend the use of CFP as a proxy environmental performance indicator for this sector.

140 Although the above studies partly shows significant and partly insignificant correlations between CFP
141 and other single point indicators. One issue that appears to tie the above studies together is that when
142 using proxy indicators for representing the overall performance of systems and services, in many
143 cases there is a considerable chance that CFP or other proxy indicators poorly correlated with the
144 overall environmental performance. As examples here of Finkbeiner (2009) presents a multitude of
145 such examples where use of carbon footprint as a proxy indicator is invalid.

146 The aim of the present work is to assess whether CFP can be used as a proxy environmental
147 performance indicator for the diverse set of products and services related to private consumption. The
148 assessment is based on analysis of consumptions patterns for 1281 urban Danish residents. Detailed
149 results from a comprehensive Personal Metabolism (PM) - LCA study of the 1281 consumption
150 patterns are reported in Kalbar et al. (2016).

151

152 **2. Methodology**

153 The present study is based on the results obtained from a coupled PM – LCA model presented in
154 detail in Kalbar et al. (2016). PM-LCA model is a specific type of consumer/lifestyle LCA (Hellweg
155 and Milà i Canals, 2014), where rather than focusing on city or country scale consumptions (Goldstein
156 et al., 2013), consumption patterns at individual levels are assessed. The PM-LCA model was used
157 to assess and quantify the impacts related to consumption patterns of urban Danish residents across
158 the entire value chain from the cradle to the grave of the goods being consumed. The model is based
159 on the outcome of a questionnaire survey analyzing the purchase and utilization of commercial goods
160 and services among urban Danish residents. The survey data covers accommodation, energy (thermal
161 energy and electricity), road transportation, air travel, food consumption, and expenditures related to
162 products and services. In addition to the consumption, recycling habits and related sustainability
163 behavioral factors were compiled via the questionnaire. In total, 1281 respondents (questionnaire
164 filled completely) were assessed as part of the study.

165 Annual household consumption patterns were estimated using the basic data compiled from the
166 completed and returned questionnaires which again were used to parameterize the generic PM model
167 capable of modelling all 1281 household consumption scenarios. The elementary flows associated
168 with the consumption scenarios were modelled and the associated environmental impacts quantified
169 with LCA. The standard one-family house was modelled in Gabi 6.0 (using Ecoinvent 2.2 database)

170 covering production of all building materials required for the construction of house. Standard unit
171 processes available in Gabi 6.0 (via Ecoinvent 2.2 database) on thermal energy (heat), electricity,
172 road transport (various fuel types and Euro standards for private cars and public buses and trains) and
173 air travel were used to compute impact potentials related with thermal energy, electricity, road
174 transport and air travel utilization in households. For estimation of the impacts associated with food
175 consumption, Simapro 8.0.4 (with Ecoinvent 3.1 database) was used. Four impact assessment
176 methods EDIP97 (Hauschild et al., 1998; Wenzel et al., 1997), EI 99(Goedkoop and Spriensma,
177 2001), CML 2001 Baseline(Guinée et al., 2001) and ReCiPe 2008(Goedkoop et al., 2008) were
178 selected for the LCIA. The impact potentials for each component of consumption (accommodation,
179 thermal energy, electricity, road transport, air travel and food) were estimated separately along with
180 the impact potential of the total consumption scenario.

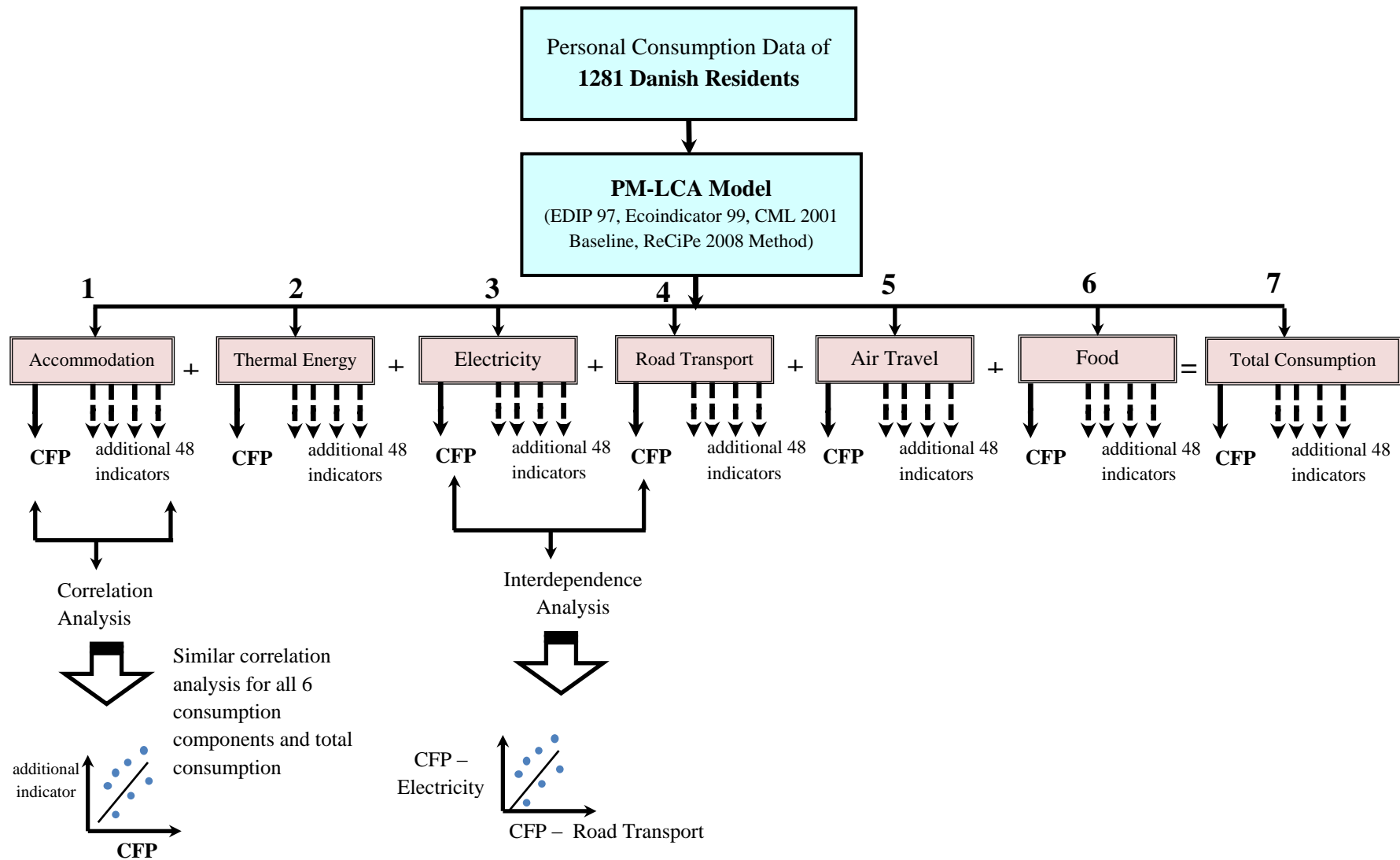
181 The climate change impact potential assessed according to the ReCiPe 2008 impact assessment
182 methodology [henceforth called Carbon FootPrint (CFP)] was considered as an independent variable,
183 and regression analyses were performed against the remaining 16 mid point indicators (water
184 depletion was not considered due to unavailability of normalization reference), 3 end point indicators
185 and one aggregated single score obtained applying the ReCiPe 2008 methodology, the 11 midpoint
186 indicators and one aggregated total score obtained applying the CML 2001 Baseline methodology,
187 the 3 endpoint indicators and one aggregated total score obtained applying the Ecoindicator 99
188 methodology, and the 11 indicators and one aggregated total score obtained applying the EDIP97
189 methodology (refer to Figure 1). Overall total 38 midpoint indicators, 6 endpoint indicators and 4
190 single score indicators were used for regression analyses (in total 48 regression analyses were
191 conducted, refer to Table 1). For all the mid-point indicators normalized values were used for
192 regression. The normalized values, endpoints and single or total scores were obtained using the most
193 context relevant normalization and weighing factors considering hierarchical perspective where
194 available. To obtain a total score in accordance with the CML 2001 Baseline method a set of
195 weighting factors from Gabi 6.0 were used(PE International, 2012).

196 The approach used to analyze correlations among the CFP and other indicators across the different
197 consumption components and total consumptions is presented in Figure 1. To derive all possible
198 linear, nonlinear and partial correlations among CFP and the other impact indicators for individual
199 and total consumption patterns, both parametric and nonparametric correlation analyses were
200 conducted. Linear correlation structures were captured through Pearson correlation coefficient (R)

201 and coefficient of determination (R^2), while nonlinear correlation structures were analyzed with
202 nonparametric rank based coefficients, Spearman's rho (ρ) and Kendall's tau (τ) (Berthouex and
203 Brown, 1994; Chen and Popovich, 2002; Reimann et al., 2011). All the correlation coefficients were
204 derived and their statistical significance were assessed for evaluation of the association between the
205 CFP and all the additional midpoint, endpoint and single score indicators (in total 48) obtained
206 applying the four LCIA methods considered for each of the consumption components and for the total
207 consumption scenario. All the computations were carried out using MATLAB®R2013b version
208 8.2.0.701.

209 As shown in Figure 1, the correlation coefficients between CFPs of each consumption component
210 along with additional 48 method specific indicators were obtained. In addition the simple and partial
211 for both linear and nonlinear correlation coefficients between the CFPs of total consumption and the
212 remaining 48 indicators of total consumption were also analyzed. Simple correlation coefficients
213 (both parametric and nonparametric) are not sufficient to explain relationships between indicators
214 particularly when causal relations are suspected among variables or indicators. Use of partial
215 correlation coefficients is an alternative, where the partial or net correlation represents actual
216 association of two analyzed indicators eliminating the effect of the remaining indicators (Spiegel and
217 Stephens, 2007). The partial correlation coefficient between CFP and any other impact indicator
218 should thus be interpreted as a particular conditional correlation coefficient; which is basically a
219 correlation between these two indicators conditioned on the set of remaining indicators.

220 As a final analysis, a set of interdependency analyses was carried out in order to assess the correlations
221 among the selected indicators for the considered consumption components assessed. Four ReCiPe
222 indicators (carbon footprint, freshwater eutrophication, terrestrial ecotoxicity, human toxicity) were
223 selected to validate the interdependency among the indicators. As an example the interdependency
224 analysis for correlation of CFP of Electricity with CFP of road transport components are highlighted
225 in Figure 1.



226

227 Figure 1: Methodology followed for investigating correlation among CFP and other impact indicators across different consumption components.

228 3. Results

229 The results obtained from the four types of regression analyses on the total consumption patterns are
230 presented in Table 1. The correlation graphs for all the 48 indicators quantified for the total
231 consumption pattern are in Figure 2. Table S1 in the Supporting Information (SI) provides detailed
232 correlation results obtained for all six consumption components along with total consumption pattern
233 results. From the results presented in Tables 1 and S1, it is observed that the linear correlation values
234 captured by R^2 follow the patterns similar to nonlinear correlation structures, obtained through
235 Spearman's (ρ) and Kendall's (τ) correlation coefficients. In nonparametric correlation analysis,
236 Spearman's rank correlation coefficient usually gives higher values than Kendall's rank correlation
237 when sufficiently large and consistent data is available for analysis.(Chen and Popovich, 2002;
238 Reimann et al., 2011) Similar observation has been made in our results as the dataset considered in
239 the current analysis is sufficiently large and consistent. These observations indicate that linear
240 correlation is predominant in the dataset in which the outliers are not affecting the correlation. Hence,
241 only R^2 values were used for further analysis and discussions.

242 The results summarized in Table S1, indicate that the CFP of each consumption component correlates
243 very well with all the other 48 indicators quantified for each of the consumption components:
244 accommodation, thermal energy, electricity, road transport, air travel and food. However, when the
245 results for the individual consumption components are aggregated to obtain the total impacts for the
246 entire consumption pattern, the CFP values for the entire consumption patterns do not necessarily
247 correlate well with all the 48 additional indicators also quantified for total consumption (refer to Table
248 1). Upon closer inspection of the results obtained from the correlation analyses of the indicators
249 quantified for the entire consumption patterns (Table 1), it is observed that the correlation between
250 the CFP is strong (R^2 in the range of 0.80 to 0.90) for the resource depletion, fossil depletion, ozone
251 depletion, particulate matter formation and photochemical oxidant formation indicators irrespective
252 of the impacts assessment method applied.

Table 1: Results obtained from a comprehensive correlation analysis of Carbon Footprint (CFP) and additional indicators quantified for total consumption patterns

Correlation between Carbon Footprint (CFP) [i.e. Recipe 1.07 Climate Change Indicator] and ¹		Metric of Correlation ^{2,3}					
		R	R ²	ρ	τ	R (partial correlation)	ρ (partial correlation)
CML2001 - Nov. 2010,	Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	0.75	0.57	0.81	0.61	0.01 [#]	-0.03 [#]
	Abiotic Depletion (ADP fossil) [MJ]	0.99	0.99	0.99	0.93	0.12	0.00 [#]
	Acidification Potential (AP) [kg SO ₂ -Equiv.]	0.92	0.85	0.93	0.77	0.00 [#]	-0.02 [#]
	Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0.72	0.52	0.75	0.56	-0.04 [#]	0.03 [#]
	Freshwater Aquatic Ecotoxicity Potential (FAETP inf.) [kg DCB-Equiv.]	0.77	0.59	0.80	0.60	-0.08	0.01 [#]
	Global Warming Potential (GWP 100 years) [kg CO ₂ -Equiv.]	1.00	1.00	1.00	0.99	0.04 [#]	0.19
	Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	0.74	0.55	0.82	0.64	-0.01 [#]	-0.02 [#]
	Marine Aquatic Ecotoxicity Potential (MAETP inf.) [kg DCB-Equiv.]	0.84	0.71	0.88	0.71	0.01 [#]	-0.11
	Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	0.98	0.96	0.98	0.89	0.03 [#]	-0.01 [#]
	Photochemical Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	0.94	0.88	0.95	0.80	-0.02 [#]	-0.06 [#]
	Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	0.89	0.79	0.91	0.74	0.00 [#]	-0.06 [#]
EI99, HA,	Human Health (DALY)	0.97	0.94	0.97	0.86	0.00 [#]	0.02 [#]
	Ecosystem [PDF*m ² *a]	-0.30	0.09	-0.35	-0.23	0.01 [#]	0.05 [#]
	Resources [MJ surplus energy]	0.99	0.97	0.99	0.91	-0.02 [#]	0.22
EDIP 1997	Acidification potential (AP) [kg SO ₂ -Equiv.]	0.95	0.90	0.96	0.83	0.06 [#]	0.01 [#]
	Ecotoxicity soil chronic [m ³ soil]	0.32	0.11	0.38	0.26	0.03 [#]	0.06 [#]
	Ecotoxicity water acute [m ³ water]	0.57	0.33	0.63	0.45	0.01 [#]	0.02 [#]
	Ecotoxicity water chronic [m ³ water]	0.54	0.29	0.59	0.42	-0.06 [#]	-0.03 [#]
	Global warming potential (GWP 100 years) [kg CO ₂ -Equiv.]	1.00	1.00	1.00	0.98	0.01 [#]	0.16
	Human toxicity air [m ³ air]	0.66	0.43	0.74	0.55	-0.01 [#]	0.02 [#]
	Human toxicity soil [m ³ soil]	0.70	0.49	0.77	0.58	-0.03 [#]	-0.05 [#]
	Human toxicity water [m ³ water]	0.80	0.65	0.83	0.64	0.00 [#]	-0.01 [#]
	Nutrient enrichment potential [kg NO ₃ ⁻ -Equiv.]	0.65	0.43	0.69	0.50	-0.07 [#]	-0.04 [#]
	Ozone depletion potential [kg R11-Equiv.]	0.96	0.93	0.97	0.85	0.01 [#]	-0.01 [#]
	Photochemical oxidant potential (low +high NO _x) [kg Ethene-Equiv.]	0.91	0.83	0.93	0.76	0.02 [#]	0.05 [#]

Correlation between Carbon Footprint (CFP) [i.e. Recipe 1.07 Climate Change Indicator] and ¹		Metric of Correlation ^{2,3}					
		R	R ²	ρ	τ	R (partial correlation)	ρ (partial correlation)
ReCiPe 1.07 Endpoint (H)	Human Health [DALY]	0.98	0.96	0.98	0.89	0.09	-0.01 [#]
	Ecosystem [Species.yr]	0.97	0.94	0.97	0.85	-0.05 [#]	0.29
	Resources [\$]	0.99	0.99	0.99	0.93	0.05 [#]	0.10
ReCiPe 1.07 Midpoint (H)	Agricultural land occupation [m ² a]	0.60	0.36	0.62	0.45	0.10	0.03 [#]
	Fossil depletion [kg oil eq]	0.99	0.99	0.99	0.93	0.06 [#]	0.01 [#]
	Freshwater ecotoxicity [kg 1,4-DB eq]	0.55	0.30	0.61	0.43	0.03 [#]	0.02 [#]
	Freshwater eutrophication [kg P eq]	0.65	0.42	0.69	0.50	0.05 [#]	0.02 [#]
	Human toxicity [kg 1,4-DB eq]	0.88	0.78	0.90	0.73	0.00 [#]	-0.06 [#]
	Ionising radiation [kg U235 eq]	0.80	0.63	0.84	0.65	-0.20	-0.03 [#]
	Marine ecotoxicity [kg 1,4-DB eq]	0.59	0.35	0.64	0.46	0.05 [#]	-0.03 [#]
	Marine eutrophication [kg N-Equiv.]	0.44	0.19	0.49	0.34	-0.05 [#]	0.03 [#]
	Metal depletion [kg Fe eq]	0.84	0.70	0.87	0.69	0.00 [#]	0.10
	Natural land transformation [m ²]	0.93	0.86	0.94	0.79	0.09	0.01 [#]
	Ozone depletion [kg CFC-11 eq]	0.98	0.96	0.98	0.89	0.02 [#]	-0.01 [#]
	Particulate matter formation [kg PM10 eq]	0.93	0.87	0.94	0.79	-0.05 [#]	0.05 [#]
	Photochemical oxidant formation [kg NMVOC]	0.89	0.78	0.92	0.76	0.00 [#]	0.04 [#]
	Terrestrial acidification [kg SO ₂ eq]	0.87	0.75	0.88	0.70	0.00 [#]	-0.05 [#]
	Terrestrial ecotoxicity [kg 1,4-DB eq]	0.41	0.17	0.45	0.32	0.10	-0.05 [#]
	Urban land occupation [m ² a]	0.69	0.48	0.76	0.57	0.00 [#]	0.06 [#]
Single Scores	Recipe Single score	0.98	0.96	0.98	0.89	0.13	0.00 [#]
	CML Single score	0.90	0.80	0.92	0.76	0.00 [#]	0.12
	EI 99 Single score	0.29	0.08	0.24	0.16	-0.04 [#]	-0.04 [#]
	EDIP 1997 (PET)	0.65	0.42	0.70	0.50	0.02 [#]	0.04 [#]

¹Normalized values were used for correlation analysis (units of indicators are provided only for better understanding of version of the LCIA method and respective indicators used)

²Pearson Correlation Coefficient (R) and Coefficient of Determination (R^2), Sperman's rho rank correlation coefficient (ρ) and Kendall's tau rank correlation coefficient (τ)

³ R^2 values are grey color shaded according to higher to lower values (more the value more the intensity of grey shade)

[#]indicates the correlation not significant at 0.01 level.

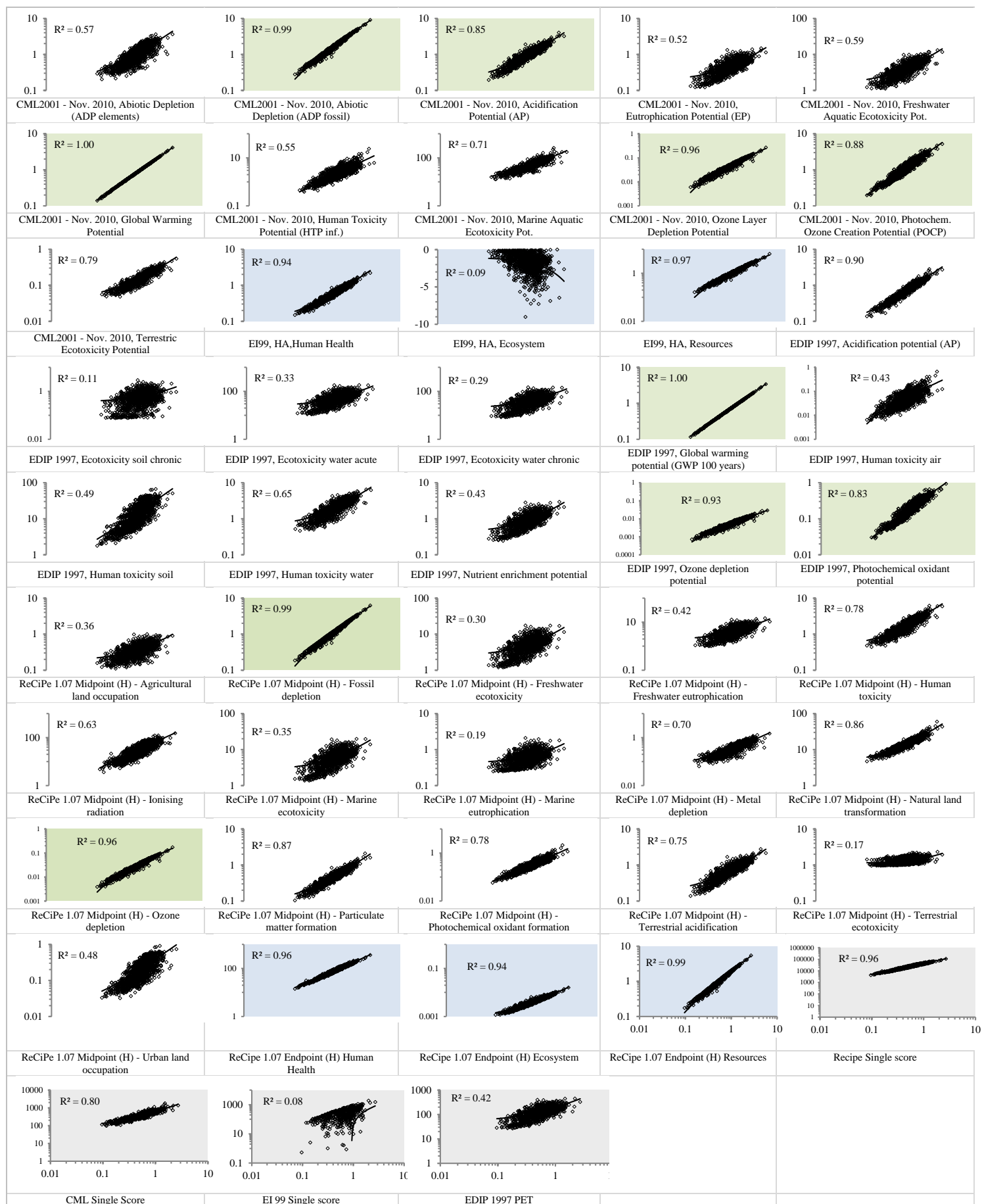


Figure 2: Correlation graphs for CFP against each of the other 48 indicators quantified for the total consumption pattern (refer to Table 1). The x-axes of each graph are ReCiPe CFP and the individual y-axes are the other indicator mentioned below each of the graphs. Pls. note that a double logarithmic plot has been used for all the correlations, except for EI99, HA, Ecosystem. Green color shaded plots represent midpoints, which all correlates strongly with CFP. Blue color shaded plots are correlations explorations between CFP and various endpoints whereas grey color plots are correlations explorations between CFP and single scores.

265 The correlations obtained for the ReCiPe CFP and the midpoint indicators quantified for the entire
 266 consumption patterns for impacts on ecosystems toxicity related impacts such as aquatic ecotoxicity,
 267 marine ecotoxicity, terrestrial ecotoxicity as well as human toxicity, marine and fresh water
 268 eutrophication and land occupation were found to be weak (R^2 in the range of 0.10 to 0.50). Further
 269 as presented in Table 1, it was found that the correlation between the CFP and the endpoint indicators
 270 obtained for the entire consumption pattern applying the Ecoindicator 99 and ReCiPe 2008 methods
 271 was strong (R^2 range 0.89 - 0.99), except for the ecosystem endpoint of the Ecoindicator 99 method.
 272 The results of correlation analyses between the ReCiPe CFP and the aggregated single scores
 273 quantified for the entire consumption patterns from the four impact assessment methods revealed that
 274 only the single score obtained applying the ReCiPe 2008 method exhibited strong correlation with
 275 the ReCiPe CFP. The last two columns of Table 1 showed Pearson's (parametric estimate to quantify
 276 linear correlation) and Spearman's (nonparametric estimate to quantify nonlinear correlation) partial
 277 correlation coefficients, which showed that most of the partial correlation values were insignificant
 278 at 0.01 level (marked with # sign), which gave better insight in individual association of all indicators
 279 with CFP, eliminating the effects of remaining indicators in terms of latent association or
 280 interdependence among them. Hence the results from partial correlation analysis assured that the CFP
 281 indicator alone does not carry the information which remaining 48 indicators carry.

282 4. Discussion

283 The impacts associated with the consumption components for accommodation (construction of
 284 house), thermal energy, electricity, road transport (cars, bus and trains), air travel and food
 285 consumption as well as the entire consumption pattern representing the sum of the consumption
 286 components were accounted for, applying a multitude of unit processes (industrial system processes,
 287 energy production processes, transportation and agricultural processes) in order to model the PM
 288 systems applying an LCA approach.

289

290 The strong correlations between the ReCiPe CFP and the 48 additional indicators within the
 291 individual consumption components (refer to Table S1) would suggest that CFP is usable as a proxy
 292 impact indicator for the individual consumption components covering consumption of commercial
 293 goods and services. However, the moment that the consumption components are aggregated into a
 294 full consumption pattern, the correlation is poor both for simple and partial correlation analyses (see

also Table 1). The aggregation of consumption components involves aggregation of impacts across different sectors such as e.g. the construction and agriculture sectors. To investigate the loss of correlation upon aggregation of the consumption component, an interdependence analysis among all indicators of individual consumption components was conducted. The correlation of impact indicators among the individual and aggregated consumption components was analyzed for four selected ReCiPe impact potentials (Climate change, Freshwater eutrophication, Terrestrial ecotoxicity and Human toxicity). The results (R^2 values) of the correlation analysis covering climate change, freshwater eutrophication, terrestrial ecotoxicity and human toxicity are presented in Table 2. The detailed results from all four types of correlation coefficients (R , R^2 , ρ , τ) are provided in Table S2 in the SI.

The result of interdependence study reveals that none of the indicators shows correlation to itself across individual consumption components and can hence be regarded as totally independent (most R^2 values between 0 to 0.2). Hence, although there is a strong correlation found between CFP and 48 indicators for each of the consumption components (refer to Table S1), no considerable correlation was observed upon aggregation of the results across consumption components in order to account for the entire consumption pattern (refer to Table 1).

The reason behind this phenomenon we seek to explain in Figure 3, where the correlation graphs for climate change versus fresh water ecotoxicity (FET) are shown for each of the individual consumption components and for the entire consumption pattern. As illustrated in the figure CFP correlate very well with FET for all 1281 results for each of the individual components, (R^2 is close to 1.00 for all consumption components). However, the slopes of the correlation graphs are different, ranging from less than 1 from thermal energy and air travel to nearly 50 for food, in accordance with the independence of the individual consumption components that was also demonstrated in the interdependence study in Table 2. Hence, when the results for the consumption components are aggregated to give the entire consumption pattern, a new and much weaker correlation emerges between CFP and FET (with $R^2=0.30$). Similar correlation graphs for CFP versus five additional ReCiPe indicators representing rather different types of environmental impact (Terrestrial ecotoxicity, Human toxicity, Ozone depletion, Fossil depletion, Freshwater eutrophication) for individual consumption components as well as the entire consumption pattern are presented in Figure S1. Together these results support the observation that although there may exist significant correlation between CFP and an environmental impact indicator at the level of an individual consumption

326 component, at the aggregation level totally new correlation situation occurs. The relation between
327 CFP and other impact indicators typically gets weaker with increasing complexity of the consumption
328 pattern.

329 These findings are in agreement with other recent efforts on correlating CFP with other impact
330 indicators. Strong correlation among some of the midpoints (resource depletion, fossil depletion,
331 ozone depletion, particulate matter formation and photochemical oxidant formation) and CFP has
332 also been reported by e.g. Van Hoof et al. (2013). The reason for these strong correlations is explained
333 by the energy use across the supply chain and the interdependency of the indicators meaning that
334 improvement in one indicator in this group is accompanied by improvement in another indicator in
335 the group.

336 The strong correlation observed between CFP and other impact indicators at the level of individual
337 consumption components may be attributed to a dominating contribution of one or a few specific unit
338 processes within each of the modelled consumption components. For example, although a wide range
339 of processes contribute to the overall impact potential originating from the construction of a house, it
340 is the production processes of aluminum window frames, concrete and steel that accounts for about
341 55-60% of the impacts in the climate change impact category, 70-75% of the human toxicity, fresh
342 water ecotoxicity, marine ecotoxicity, freshwater eutrophication impact categories and 55% of the
343 impact potential in the terrestrial ecotoxicity impact category. The impacts from these three
344 production processes are all driven by their consumption of large amounts of resources and energy
345 (the latter of which is mainly generated from combustion of fossil fuels). Previous work has
346 demonstrated a significant correlation between CFP and other indicators for the metal and energy
347 production processes (fossil as well as some renewable energy processes).(Laurent et al., 2012) Such
348 significant correlation between CFP and other indicators translates into the observed correlations in
349 this study the unit process or component level of the construction of house, as the impacts are tied to
350 metal and energy production.

351

352 Table 2: Result of interdependence study – correlation among indicators of each consumption component

Recipe 1.07 Climate Change Indicator									
			1	2	3	4	5	6	7
Recipe 1.07 Climate Change Indicator	Correlation between		Accommodation	Thermal Energy	Electricity	Road Transport	Air Travel	Food	Total Consumption
	Accommodation	R^2	1.00	0.31	0.19	0.01	0.00 [#]	0.00 [#]	0.34
	Thermal Energy			1.00	0.12	0.00 [#]	0.00 [#]	0.02	0.45
	Electricity				1.00	0.02	0.00 [#]	0.01 [#]	0.26
	Road Transport					1.00	0.00 [#]	0.04	0.31
	Air Travel						1.00	0.00 [#]	0.15
	Food							1.00	0.10
	Total Consumption								1.00
Recipe 1.07 Freshwater Eutrophication									
Recipe 1.07 Freshwater Eutrophication	Correlation between		Accommodation	Thermal Energy	Electricity	Road Transport	Air Travel	Food	Total Consumption
	Accommodation	R^2	1.00	0.31	0.19	0.01	0.00 [#]	0.00 [#]	0.12
	Thermal Energy			1.00	0.12	0.00 [#]	0.00 [#]	0.02	0.10
	Electricity				1.00	0.01	0.00 [#]	0.00 [#]	0.13
	Road Transport					1.00	0.00 [#]	0.03	0.22
	Air Travel						1.00	0.00 [#]	0.00
	Food							1.00	0.80
	Total Consumption								1.00
Recipe 1.07 Terrestrial Ecotoxicity									
Recipe 1.07 Terrestrial Ecotoxicity	Correlation between		Accommodation	Thermal Energy	Electricity	Road Transport	Air Travel	Food	Total Consumption
	Accommodation	R^2	1.00	0.31	0.19	0.01	0.00 [#]	0.01	0.03
	Thermal Energy			1.00	0.12	0.00 [#]	0.00 [#]	0.02	0.04
	Electricity				1.00	0.02	0.00 [#]	0.00 [#]	0.03
	Road Transport					1.00	0.00 [#]	0.06	0.10
	Air Travel						1.00	0.00 [#]	0.00 [#]
	Food							1.00	0.97
	Total Consumption								1.00
Recipe 1.07 Human Toxicity									
Recipe 1.07 Human Toxicity	Correlation between		Accommodation	Thermal Energy	Electricity	Road Transport	Air Travel	Food	Total Consumption
	Accommodation	R^2	1.00	0.31	0.19	0.01	0.00 [#]	0.00 [#]	0.33
	Thermal Energy			1.00	0.12	0.00 [#]	0.00 [#]	0.02	0.21
	Electricity				1.00	0.01	0.00 [#]	0.00 [#]	0.31
	Road Transport					1.00	0.00 [#]	0.04	0.49
	Air Travel						1.00	0.00 [#]	0.01
	Food							1.00	0.29
	Total Consumption								1.00

353 #indicates the correlation is not significant at 0.01 level

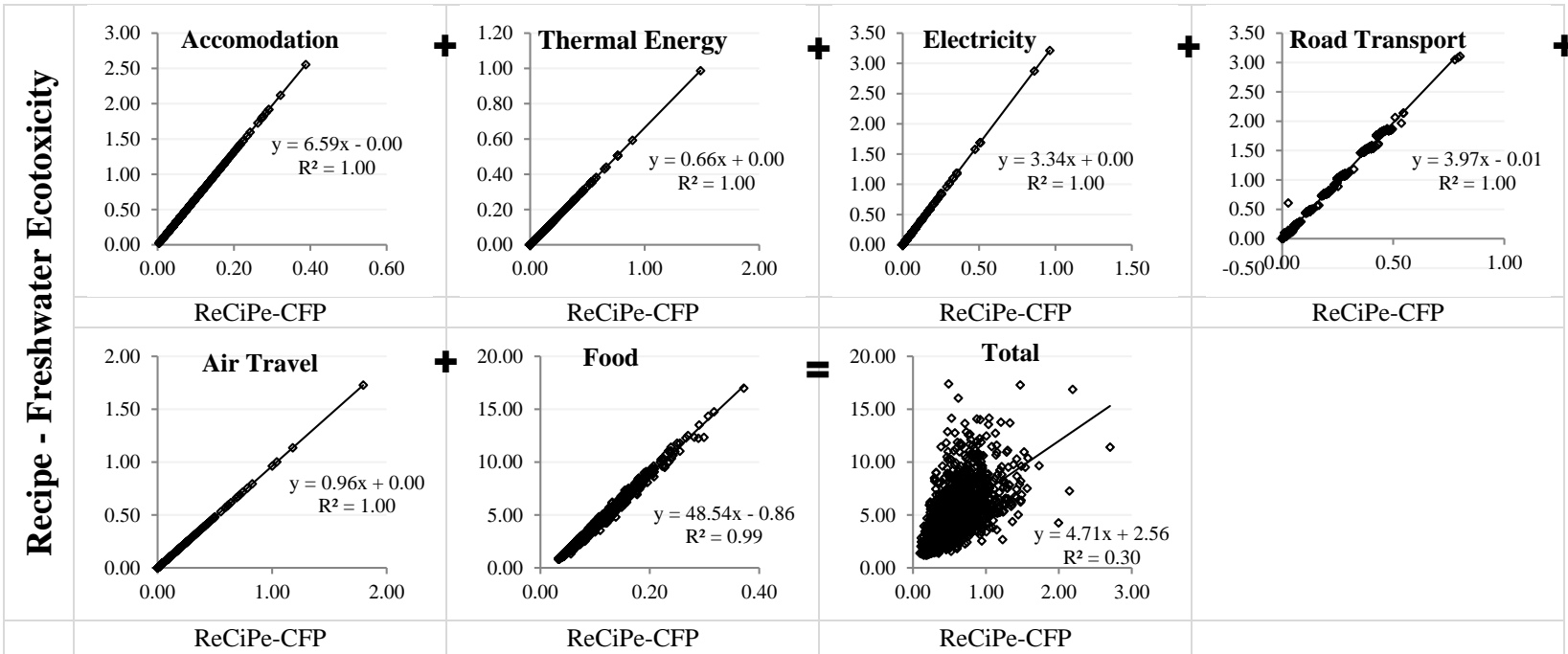


Figure 3: Correlation graphs showing effect of aggregation on the correlation between CFP and Freshwater Ecotoxicity (FET) at the total consumption level (x-axis – CFP and y-axis FET)

364 At the aggregation level of the entire consumption pattern the complexity of the modelled product
365 systems increases considerable and the correlations between the different impact indicators thus gets
366 weaker and in some cases even is lost for many impact categories. These observations are illustrated
367 in Figure 3 and Figure S1. Nevertheless, it was shown that significant correlations still exist between
368 CFP and endpoints as well as between CFP and most of the aggregated single scores obtained from
369 four different LCIA methods (refer to Table 1). Particularly, significant correlation is observed
370 between CFP and the ReCiPe endpoints as well as the ReCiPe single score. Analysis of the
371 correlations between midpoint impact categories reveals that, the impact categories accounting for
372 impacts related to agriculture land occupation, human toxicity, ecotoxicity (freshwater and
373 terrestrial), eutrophication (freshwater and marine) all exhibit poor correlation with CFP, which is in
374 alignment with findings from previous studies (Laurent et al., 2012, 2010; Van Hoof et al., 2013).
375 One of the reasons why this weak correlation is not observed in the endpoint results is most likely the
376 poor representation of these midpoint impacts in the damage modelling approach applied by the
377 ReCiPe method meaning that the endpoint results are dominated by the climate change impacts and
378 hence correlate well with CFP. Van Hoof et al. (2013) discussed the issues related with indicator
379 selection in LCA and concluded that endpoint indicators may not always be suitable for providing
380 suitable decision support, and in a recent analysis of LCIA methods and development of
381 recommendations of good practice, none of the endpoint methods were deemed mature for
382 recommendation by the European Commission (Hauschild et al., 2013). Therefore, it is
383 recommended by Van Hoof et al. (2013) to conduct contribution analyses of midpoints contribution
384 to endpoints and based on this analysis identify the midpoints that contribute most to the endpoints.
385 The midpoints identified are then the midpoints to be chosen for decision support and policymaking
386 based on simplified LCA result sets is warranted. The risk associated with the use of CFP as a proxy
387 environmental impact indicator was also highlighted by R  s et al. (2013) in relation to assessment
388 of meat production from ruminants.

389 One of the limitations of our study is that water depletion indicator was not included in the assessment
390 due to unavailability of normalization reference implemented in the software used to derive the
391 indicators. This limitation actually stems from the LCIA methods such as ReCiPe that have not
392 provided the normalization references for water depletion impact category. Recently, Benini et al.
393 (2014) reported normalization references for the water depletion impact category. However, use of
394 water depletion impacts are not well modelled in the present LCIA methods (Hauschild, et al., 2013)
395 and different software differ in terms implementation extent and approach of characterization factors

396 for water depletion (Benini et al., 2014). Adding water depletion impacts to our study would simply
397 add further uncertainty to the results. Also, we do not envisage any major effects of the omission of
398 water depletion indicators on the conclusions drawn from the present analysis, as we have covered a
399 sufficient number and hence diverse set of indicators (agriculture land occupation, human toxicity,
400 ecotoxicity (freshwater and terrestrial), eutrophication (freshwater and marine)) to support our
401 findings on which our conclusions have been drawn.

402 Our study, which targets assessment of urban consumption and related impact potentials, showed that
403 CFP alone obviously cannot be used as a proxy for the overall environmental footprint in relation to
404 assessment of complex (i.e. systems where the impacts are not driven by a few activities like
405 consumption of energy and/or a narrow palette of resources) product systems involving a multitude
406 of industrial sectors. This finding opposes the use of CFP as environmental performance indicators
407 for complex systems such as urban systems and system driven by complex subjective (consumer)
408 preferences such as the consumption patterns of urban residents targeted in this paper.

409 For complex systems such as urban consumption, where, as stated above CFP cannot be used for
410 representing diverse environmental impacts, Principal Components Analysis (PCA) could be used to
411 reduce the number of indicators from the chosen LCIA method. Recently, Lasvaux et al. (2016)
412 shown such an analysis carried out for construction sector and concluded that reduced number of
413 indicators in terms of principal components (which represent 90-95% of the variance) can be obtained
414 for each of the LCIA method using PCA.

415 Steinmann et al. (2016) further demonstrated a PCA combined with correlation analysis method to
416 reduce the number of indicators and reported a large amount of redundancy in a set of 135 chosen
417 indicators from available in LCIA methods. Out of 135 indicators, six (climate change, land use,
418 ozone depletion, acidification and eutrophication, marine ecotoxicity terrestrial ecotoxicity) best
419 indicators representing cumulative 92% of variance were identified. From the list of these six
420 indicators, it is seen that CFP represents only part of the variation of the system impacts.

421 The finding from our study and these recent efforts shows that, it is essential to go one step further
422 and hence beyond conventional analysis while dealing with sustainability assessment of complex
423 systems. Methods and tools such as PCA and Multiple Criteria Decision Making (MCDM) play a
424 critical role while providing decision support in such situations. PCA and MCDM are on the other
425 hand complex data analysis approaches and not applicable by the average life cycle practitioner. We

therefore suggest that techniques such as PCA and MCDM should be included in the product system modelling software and where these analyses can be performed according to a set of predefined guidelines.

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 550

Supporting Information

for

Can carbon footprint serve as proxy of the environmental burden from urban consumption patterns?

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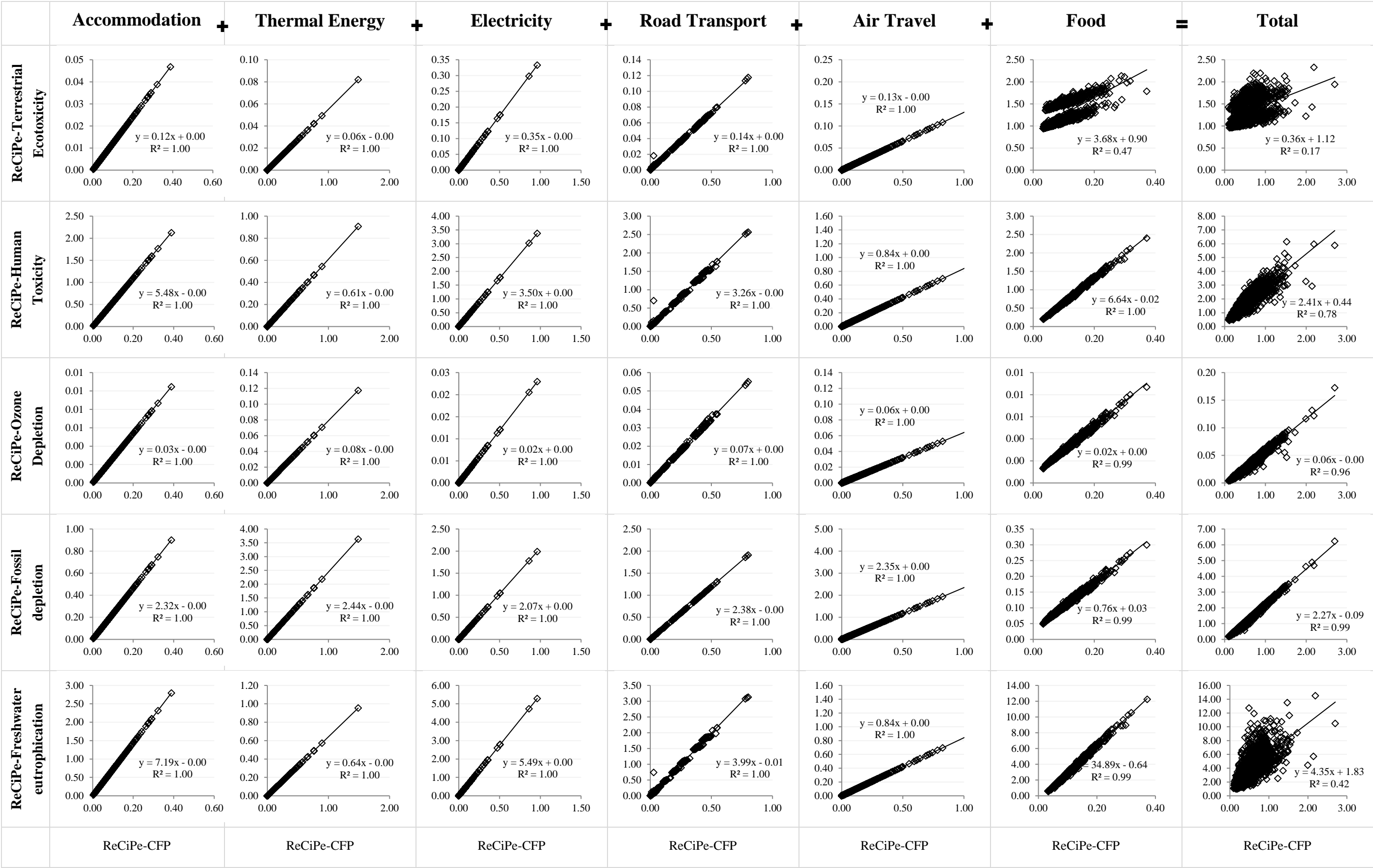



Figure S1: Correlation graphs showing effect of aggregation on the correlation between CFP and other impact indicators at the total consumption level.

Table S1: Results of correlation analysis between the ReCiPe Carbon Footprint (CFP) and the additional indicators considered in our study at the level of individual consumption components and for the total consumption.

Correlation between Carbon Footprint (CFP) [i.e. Recipe 1.07 Climate Change Indicator] and ¹					Metric of Correlation ^{2,3}																				Correlation Coefficient							
																									High				Low			
					1	0.75	0.5	0.25	0.05																							
					Accommodation				Thermal Energy				Electricity				Road Transport				Air Travel				Food				Total Consumption			
					R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ				
CML2001 - Nov. 2010,	Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.96	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.95	0.75	0.57	0.81	0.61				
	Abiotic Depletion (ADP fossil) [MJ]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.93	0.99	0.99	0.99					
	Acidification Potential (AP) [kg SO2-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.95	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.95	0.92	0.85	0.93	0.77				
	Eutrophication Potential (EP) [kg Phosphate-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.95	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.72	0.52	0.75	0.56				
	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.77	0.59	0.80	0.60					
	Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99				
	Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.99	0.95	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.74	0.55	0.82	0.64				
	Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.84	0.71	0.88	0.71				
	Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.94	0.98	0.96	0.98	0.89			
	Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.94	0.88	0.95	0.80					
Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	1.00	0.97	0.94	0.97	0.85	0.89	0.79	0.91	0.74				
EI99, HA,	Human Health (DALY)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.94	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.97	0.94	0.97	0.86					
	Ecosystem [PDF*m2*a]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.95	1.00	1.00	1.00	1.00	-1.00	0.99	-1.00	-0.95	-0.30	0.09	-0.35	-0.23				
	Resources [MJ surplus energy]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.94	0.99	0.97	0.99	0.91				
EDIP	Acidification potential (AP) [kg SO2-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.95	0.95	0.90	0.96	0.83				
	Ecotoxicity soil chronic [m3 soil]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.64	0.42	0.71	0.57	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.32	0.11	0.38	0.26				

Correlation between Carbon Footprint (CFP) [i.e. Recipe 1.07 Climate Change Indicator] and ¹		Metric of Correlation ^{2,3}																											
		Accommodation				Thermal Energy				Electricity				Road Transport				Air Travel				Food				Total Consumption			
R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ		
1997	Ecotoxicity water acute [m3 water]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.94	0.57	0.33	0.63	0.45	
	Ecotoxicity water chronic [m3 water]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.94	0.54	0.29	0.59	0.42	
	Global warming potential (GWP 100 years) [kg CO2-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	
	Human toxicity air [m3 air]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.94	0.99	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.66	0.43	0.74	0.55	
	Human toxicity soil [m3 soil]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.92	0.98	0.89	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.96	0.70	0.49	0.77	0.58	
	Human toxicity water [m3 water]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.95	0.80	0.65	0.83	0.64	
	Nutrient enrichment potential [kg NO3-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.99	0.92	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.65	0.43	0.69	0.50		
	Ozone depletion potential [kg R11-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.94	0.96	0.93	0.97	0.85	
	Photochemical oxidant potential (Low +high NOx) [kg Ethene-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.91	0.83	0.93	0.76		
ReCiPe 1.07 Endpoint (H)	Human Health [DALY]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.96	0.98	0.89		
	Ecosystem [Species.yr]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.97	0.94	0.97	0.85			
	Resources [\$]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.94	0.99	0.99	0.99	0.93	
ReCiPe 1.07 Midpoint (H)	Agricultural land occupation [m2a]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	0.99	0.99	1.00	0.95	0.60	0.36	0.62	0.45	
	Fossil depletion [kg oil eq]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.93	0.99	0.99	0.99	0.93	
	Freshwater ecotoxicity [kg 1,4-DB eq]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.95	0.55	0.30	0.61	0.43	
	Freshwater eutrophication [kg P eq]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.95	0.65	0.42	0.69	0.50	
	Human toxicity [kg 1,4-DB eq]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.88	0.78	0.90	0.73		
	Ionising radiation [kg U235 eq]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.94	1.00	1.00	1.00	1.00	1.00	0.98	0.97	0.98	0.89	0.80	0.63	0.84	0.65
	Marine ecotoxicity [kg 1,4-DB eq]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.94	0.59	0.35	0.64	0.46	

Correlation between Carbon Footprint (CFP) [i.e. Recipe 1.07 Climate Change Indicator] and ¹					Metric of Correlation ^{2,3}																												Correlation Coefficient				
																																	High  Low				
										1	0.75	0.5	0.25	0.05																							
					Accommodation				Thermal Energy				Electricity				Road Transport				Air Travel				Food				Total Consumption								
					R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ	R	R ²	ρ	τ					
	Marine eutrophication [kg N-Equiv.]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.92	0.97	0.86	1.00	1.00	1.00	1.00	0.99	0.98	0.99	0.92	0.44	0.19	0.49	0.34								
	Metal depletion [kg Fe eq]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.84	0.70	0.87	0.69								
	Natural land transformation [m2]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	0.95	0.91	0.93	0.80	0.93	0.86	0.94	0.79									
	Ozone depletion [kg CFC-11 eq]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.94	0.98	0.96	0.98	0.89									
	Particulate matter formation [kg PM10 eq]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.97	0.99	0.91	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.93	0.87	0.94	0.79									
	Photochemical oxidant formation [kg NMVOC]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.92	0.97	0.88	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.89	0.78	0.92	0.76									
	Terrestrial acidification [kg SO2 eq]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.94	1.00	1.00	1.00	1.00	1.00	1.00	0.95	0.87	0.75	0.88	0.70									
	Terrestrial ecotoxicity [kg 1,4-DB eq]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	0.69	0.47	0.75	0.60	0.41	0.17	0.45	0.32								
	Urban land occupation [m2a]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.95	0.69	0.48	0.76	0.57								
Single Scores	Recipe Single score	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.96	0.98	0.89									
	CML Single score	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.90	0.80	0.92	0.76										
	EI 99 Single score	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	-1.00	0.99	-1.00	-0.94	0.29	0.08	0.24	0.16									
	EDIP 1997 (PET)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.99	0.94	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.94	0.65	0.42	0.70	0.50								

¹Normalized values were used for correlation analysis (units of indicators are provided only for better understanding of version of the LCIA method and respective indicators used)

²Pearson Correlation Coefficient (R) and Coefficeint of Determination (R²), Sperman’s rho rank correlation coefficient (ρ) and Kendall’s tau rank correlation coefficient (τ)

³All the correlation values reported in this table are significant at 0.01 level.

Table S2: Result of interdependence study – Correlation among indicators of each consumption component
 Pearson Correlation Coefficient; Coefficient of Determination (R^2); Spearman's rank correlation coefficient (ρ) and Kendall's rank correlation coefficient (τ)

#indicates the correlation not significant at 0.01 level.

Recipe 1.07 Climate Change Indicator								
Correlation between		Accommodation	Thermal Energy	Electricity	Road Transport	Air Travel	Food	Total Consumption
Recipe 1.07 Climate Change Indicator	Accommodation	1.00	0.56	0.44	0.10	0.02 [#]	0.07 [#]	0.58
	Thermal Energy		1.00	0.34	0.06 [#]	-0.02 [#]	0.13	0.67
	Electricity			1.00	0.12	-0.05 [#]	0.07 [#]	0.51
	Road Transport				1.00	-0.04 [#]	0.19	0.55
	Air Travel					1.00	-0.05 [#]	0.39
	Food						1.00	0.32
	Total Consumption							1.00
	Accommodation	1.00	0.31	0.19	0.01	0.00	0.00	0.34
	Thermal Energy		1.00	0.12	0.00	0.00	0.02	0.45
	Electricity			1.00	0.02	0.00	0.01	0.26
	Road Transport				1.00	0.00	0.04	0.31
	Air Travel					1.00	0.00	0.15
	Food						1.00	0.10
	Total Consumption							1.00
	Accommodation	1.00	0.51	0.45	0.13	0.07 [#]	0.12	0.58
	Thermal Energy		1.00	0.45	0.08	0.03 [#]	0.20	0.61
	Electricity			1.00	0.13	-0.06 [#]	0.13	0.51
	Road Transport				1.00	-0.01 [#]	0.23	0.59
	Air Travel					1.00	-0.05 [#]	0.29
	Food						1.00	0.37
	Total Consumption							1.00
	Accommodation	1.00	0.36	0.33	0.09	0.05 [#]	0.08	0.41
	Thermal Energy		1.00	0.36	0.05	0.02 [#]	0.13	0.45
	Electricity			1.00	0.10	-0.04 [#]	0.09	0.37
	Road Transport				1.00	-0.01 [#]	0.16	0.42
	Air Travel					1.00	-0.04 [#]	0.21
	Food						1.00	0.25
	Total Consumption							1.00

Recipe 1.07 Freshwater Eutrophication									
Recipe 1.07 Freshwater Eutrophication	Correlation between		Accomm odation	Thermal Energy	Electricit y	Road Transpo rt	Air Travel	Food	Total Consum ption
	Accommodatio n	R	1.00	0.56	0.44	0.10	0.02 [#]	0.06 [#]	0.35
	Thermal Energy			1.00	0.34	0.06 [#]	-0.02 [#]	0.12	0.32
	Electricity				1.00	0.12	-0.05 [#]	0.06 [#]	0.36
	Road Transport					1.00	-0.04 [#]	0.18	0.47
	Air Travel						1.00	-0.04 [#]	0.00 [#]
	Food							1.00	0.89
	Total Consumption								1.00
	Accommodatio n	R ²	1.00	0.31	0.19	0.01	0.00	0.00	0.12
	Thermal Energy			1.00	0.12	0.00	0.00	0.02	0.10
	Electricity				1.00	0.01	0.00	0.00	0.13
	Road Transport					1.00	0.00	0.03	0.22
	Air Travel						1.00	0.00	0.00
	Food							1.00	0.80
	Total Consumption								1.00
	Accommodatio n	ρ	1.00	0.51	0.45	0.13	0.07 [#]	0.11	0.37
	Thermal Energy			1.00	0.45	0.08	0.03 [#]	0.19	0.34
	Electricity				1.00	0.13	-0.06 [#]	0.12	0.37
	Road Transport					1.00	-0.01 [#]	0.23	0.50
	Air Travel						1.00	-0.05 [#]	-0.01 [#]
	Food							1.00	0.88
	Total Consumption								1.00
	Accommodatio n	τ	1.00	0.36	0.33	0.09	0.05 [#]	0.07	0.25
	Thermal Energy			1.00	0.36	0.06	0.02 [#]	0.13	0.23
	Electricity				1.00	0.10	-0.04 [#]	0.08	0.26
	Road Transport					1.00	0.00 [#]	0.15	0.34
	Air Travel						1.00	-0.04 [#]	0.00 [#]
	Food							1.00	0.70
Total Consumption								1.00	

Table S2 Continued.....

Recipe 1.07 Terrestrial Ecotoxicity								
Correlation between		Accomm odation	Thermal Energy	Electricit y	Road Transpo rt	Air Travel	Food	Total Consum ption
Accommodatio n	R	1.00	0.56	0.44	0.10	0.02 [#]	0.07	0.16
Thermal Energy			1.00	0.34	0.06 [#]	-0.02 [#]	0.13	0.20
Electricity				1.00	0.12	-0.05 [#]	0.06 [#]	0.18
Road Transport					1.00	-0.04 [#]	0.24	0.32
Air Travel						1.00	-0.06 [#]	0.00 [#]
Food							1.00	0.99
Total Consumption								1.00
Accommodatio n	R ²	1.00	0.31	0.19	0.01	0.00	0.01	0.03
Thermal Energy			1.00	0.12	0.00	0.00	0.02	0.04
Electricity				1.00	0.02	0.00	0.00	0.03
Road Transport					1.00	0.00	0.06	0.10
Air Travel						1.00	0.00	0.00
Food							1.00	0.97
Total Consumption								1.00
Accommodatio n	ρ	1.00	0.51	0.45	0.13	0.07 [#]	0.10	0.19
Thermal Energy			1.00	0.45	0.08	0.03 [#]	0.17	0.23
Electricity				1.00	0.13	-0.06 [#]	0.11	0.22
Road Transport					1.00	-0.01 [#]	0.25	0.34
Air Travel						1.00	-0.08	-0.04 [#]
Food							1.00	0.98
Total Consumption								1.00
Accommodatio n	τ	1.00	0.36	0.33	0.09	0.05 [#]	0.07	0.13
Thermal Energy			1.00	0.36	0.05	0.02 [#]	0.12	0.16
Electricity				1.00	0.10	-0.04 [#]	0.08	0.15
Road Transport					1.00	-0.01 [#]	0.17	0.23
Air Travel						1.00	-0.06	-0.02 [#]
Food							1.00	0.89
Total Consumption								1.00

Recipe 1.07 Terrestrial Ecotoxicity

Table S2 Continued.....

Recipe 1.07 Human Toxicity									
Recipe 1.07 Human Toxicity	Correlation between		Accomm odation	Thermal Energy	Electricit y	Road Transpo rt	Air Travel	Food	Total Consum ption
	Accommodatio n	R	1.00	0.56	0.44	0.10	0.02 [#]	0.06 [#]	0.58
	Thermal Energy			1.00	0.34	0.06 [#]	-0.02 [#]	0.13	0.45
	Electricity				1.00	0.12	-0.05 [#]	0.07 [#]	0.56
	Road Transport					1.00	-0.04 [#]	0.19	0.70
	Air Travel						1.00	-0.04 [#]	0.08
	Food							1.00	0.53
	Total Consumption								1.00
	Accommodatio n	R ²	1.00	0.31	0.19	0.01	0.00	0.00	0.33
	Thermal Energy			1.00	0.12	0.00	0.00	0.02	0.21
	Electricity				1.00	0.01	0.00	0.00	0.31
	Road Transport					1.00	0.00	0.04	0.49
	Air Travel						1.00	0.00	0.01
	Food							1.00	0.29
	Total Consumption								1.00
	Accommodatio n	ρ	1.00	0.51	0.45	0.13	0.07 [#]	0.12	0.55
	Thermal Energy			1.00	0.45	0.08	0.03 [#]	0.19	0.43
	Electricity				1.00	0.13	-0.06 [#]	0.12	0.51
	Road Transport					1.00	-0.01 [#]	0.23	0.71
	Air Travel						1.00	-0.05 [#]	0.06 [#]
	Food							1.00	0.56
	Total Consumption								1.00
	Accommodatio n	τ	1.00	0.36	0.33	0.09	0.05 [#]	0.08	0.39
	Thermal Energy			1.00	0.36	0.06	0.02 [#]	0.13	0.31
	Electricity				1.00	0.10	-0.04 [#]	0.09	0.37
	Road Transport					1.00	0.00 [#]	0.16	0.51
	Air Travel						1.00	-0.04 [#]	0.04 [#]
	Food							1.00	0.40
Total Consumption								1.00	